PROGRESS REPORT

PR 91565-430-2

For Month of August 1962

DEVELOPMENT OF AUXILIARY ELECTRIC POWER SUPPLY SYSTEM

NASA Contract NAS 3-2550

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NASA PROGRESS REPORT

INTRODUCTION

This report covers the work accomplished by Vickers Incorporated under NASA Contract NAS3-2550 during the month of August, 1962. The objectives of this program are to conduct an engineering study culminating in the design of a hydrogen-oxygen space power system and to conduct preliminary testing on critical components of the system.

PROGRAM PLAN

The program plan for this project was described in the progress report for July 1962. No changes to the program plan have been made since that report was issued.

PROGRAM SCHEDULE

The program schedule is shown in Fig. 1. In addition to showing the overall schedule for the program, Fig. 1 also indicates the percent of completion of each phase of the program and the amount of scheduled effort expended as of the end of this reporting period.

WORK ACCOMPLISHED

Parametric Studies

a. Cycle Analysis

Five different cycles and power regulation methods have been investigated. These cycles are:

1. Variable admission

PROGRAM SCHEDULE NASA CONTRACT NAS 3-2550

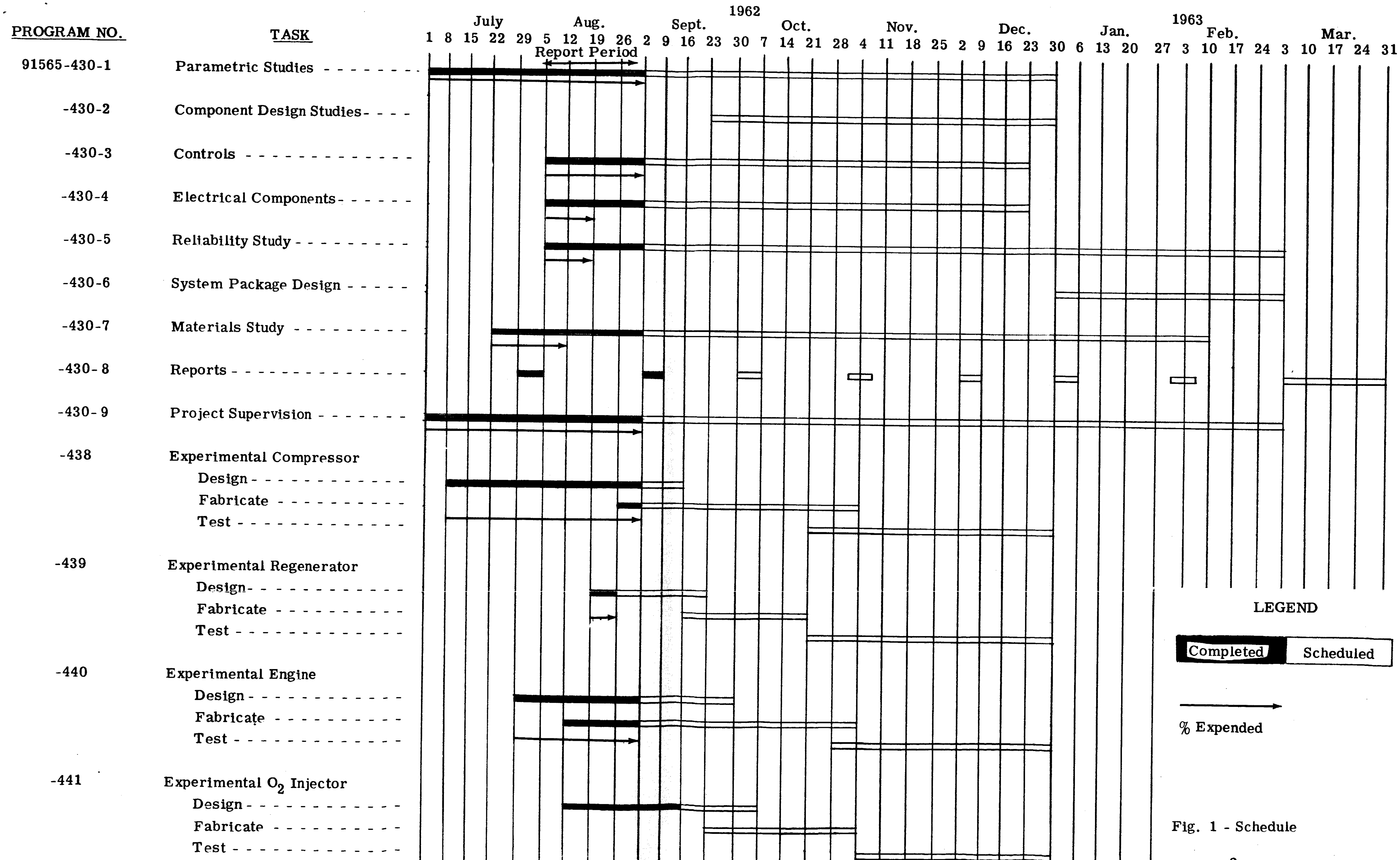


Fig. 1 - Schedule

2. Constant duration, variable phase hydrogen valve
3. Otto cycle with variable clearance volume
4. Otto cycle with variable exhaust pressure, and
5. Otto cycle with variable hydrogen inlet pressure

For these cycles, analysis was based on the idealized indicator diagrams shown in Fig. 2. With saturated hydrogen and oxygen vapor at 15 psia compression of the hydrogen and oxygen is necessary. For each of the cycles the BSPC is shown in Figure 3 and the BSPC for operation with super critical hydrogen and oxygen where no compression work is necessary is shown in Figure 4. In all cases it was assumed that combustion occurs at constant volume.

The variable admission engine required the variable phase overlapping poppet valves to regulate the hydrogen flow into the engine. To cover the required power range an engine of approximately 1.5 cubic inches displacement with a 5% clearance volume would be necessary. This engine is less suited to the narrow power range specified for this program than are versions of the Otto cycle. It is more attractive for wider power ranges where most of the operation is at the low power end of the range.

The constant duration, variable phase hydrogen valve was analysed because of the simplicity of the valve mechanism. The cam would be of constant duration but would have variable phasing with the crank shaft. To obtain the power required, an engine of approximately 1.5 cubic inches displacement with a 5% clearance volume would be necessary. This engine would have a 13% increase in BSPC at low power with only a 1% increase at a 2 KW load and no increase at a 3 KW load as compared with the variable admission cycle. This engine cycle has no advantages over the variable admission cycle other than mechanical simplicity.

Fig. 2

INDICATOR CARDS FOR THE CYCLES ANALYZED

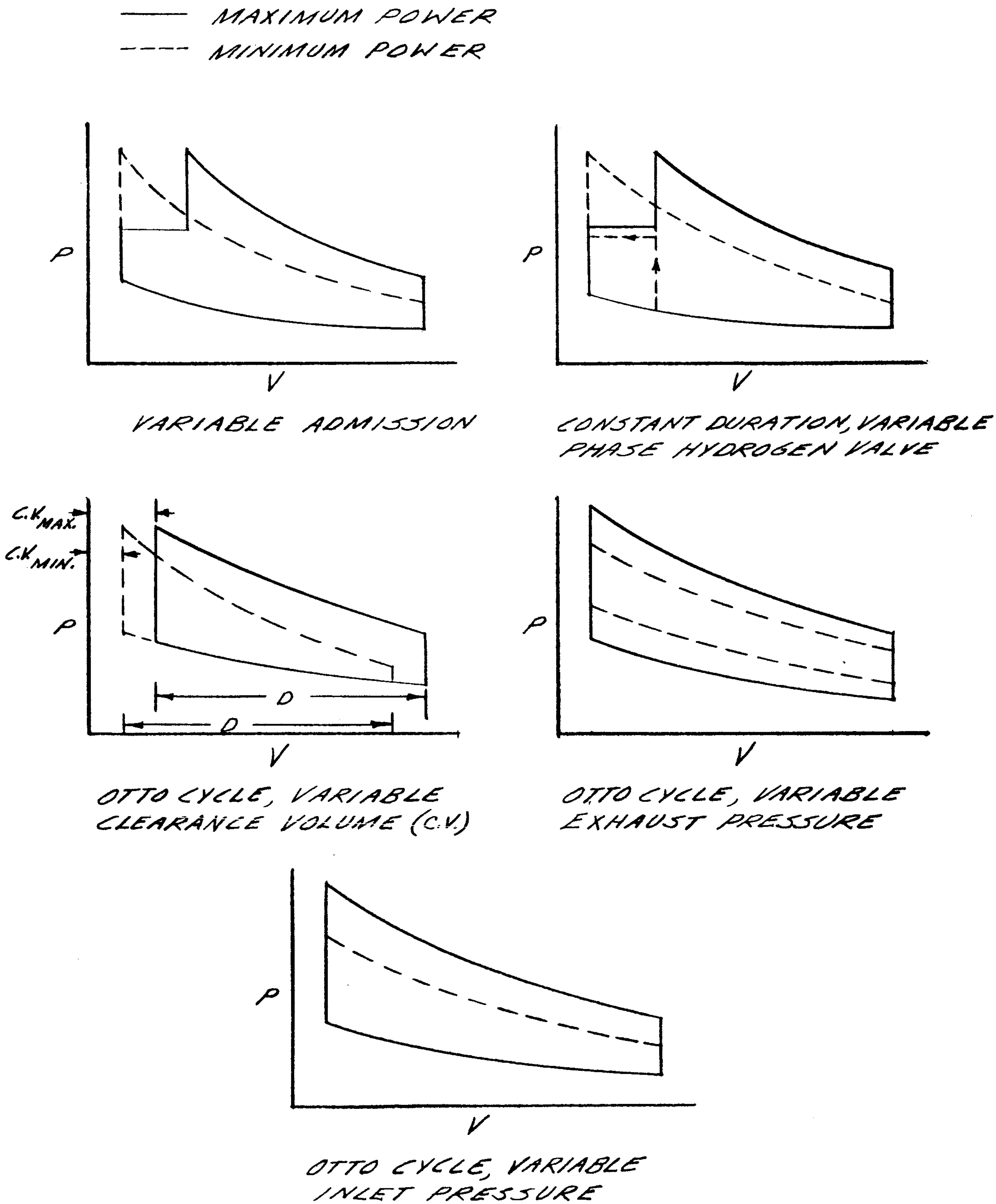


Fig. 3

SATURATED H_2 AND O_2 VAPOR AT 15 PSIA

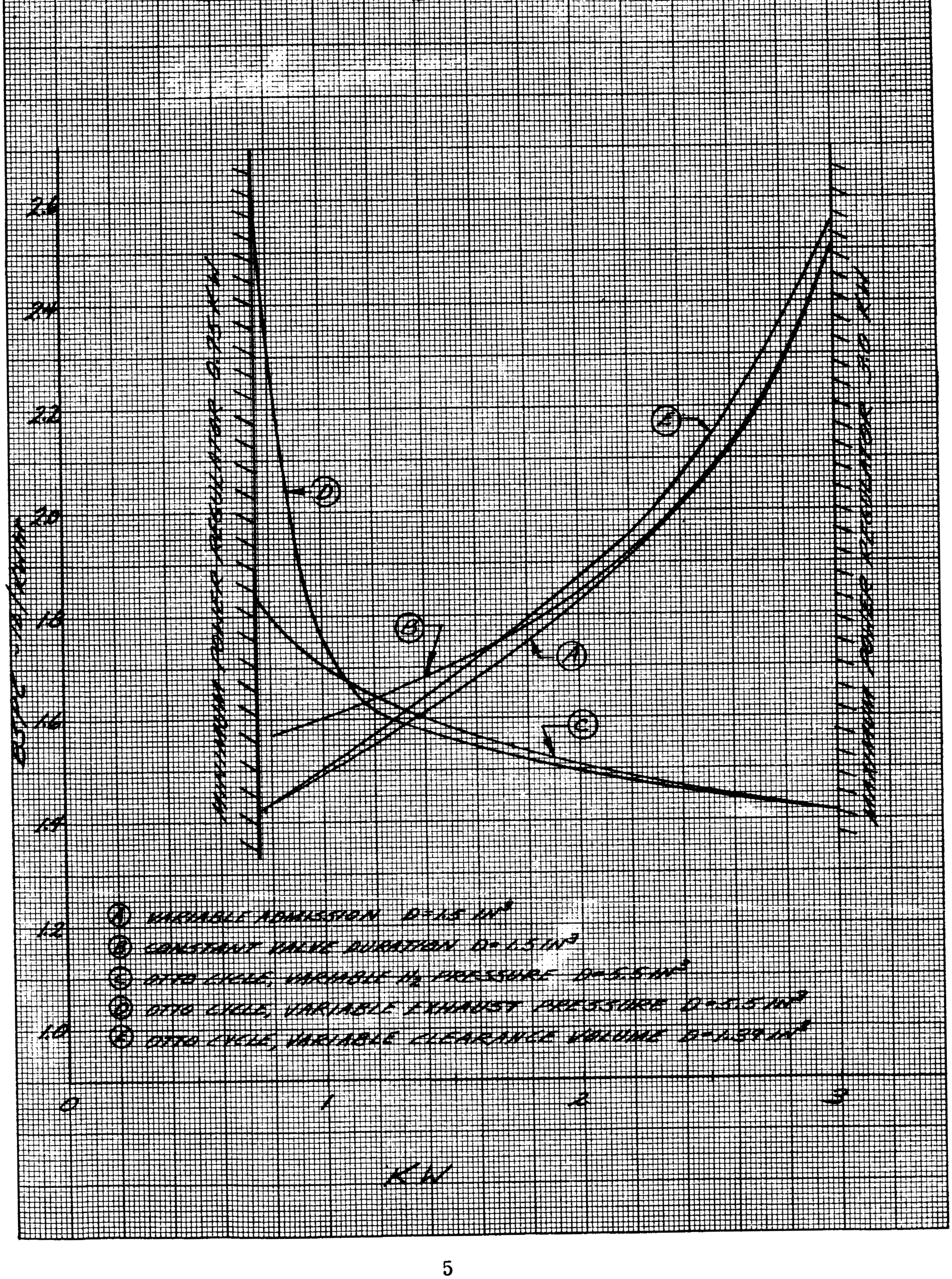
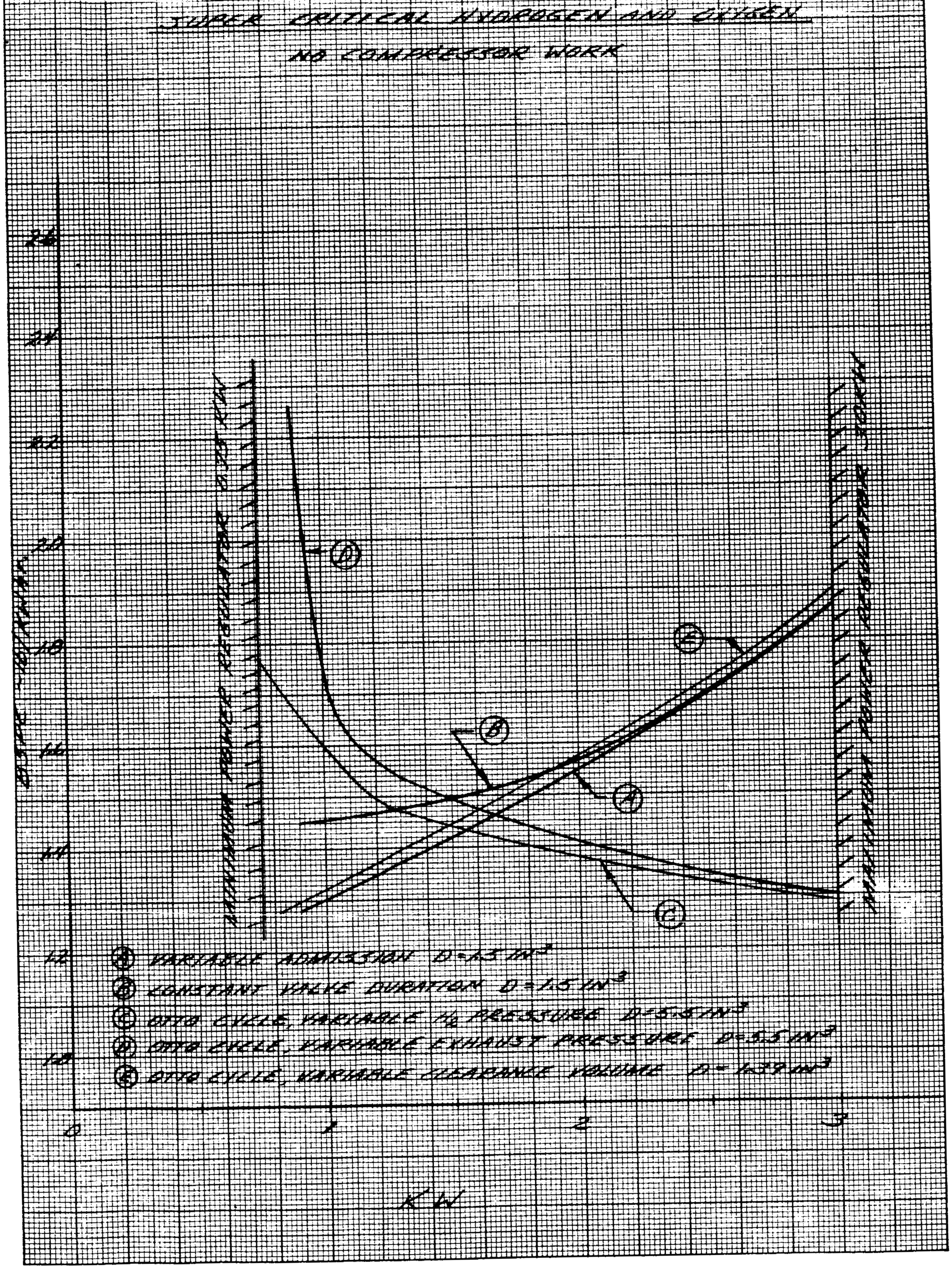


Fig. 4



SUPER CRITICAL HYDROGEN AND OXYGEN
NO COMPRESSOR WORK
MINIMUM POWER REGULATOR STOP KW
MAXIMUM POWER REGULATOR STOP KW
A
B
C
D
E
(A) VARIABLE ADMISSION D=1.5 IN³
(B) CONSTANT VALVE DURATION D=1.5 IN³
(C) OTTO CYCLE, VARIABLE H₂ PRESSURE D=5.5 IN³
(D) OTTO CYCLE, VARIABLE EXHAUST PRESSURE D=5.5 IN³
(E) OTTO CYCLE, VARIABLE CLEARANCE VOLUME D=1.39 IN³
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
1
2
3
KW

Three variations of the Otto cycle were investigated. The Otto cycle has a 15^0 duration hydrogen valve which opens 15^0 BTDC and all the required hydrogen is admitted into the clearance volume. The oxygen is admitted at TDC and combustion takes place at TDC or very close to TDC. In this cycle analysis it was assumed combustion takes place at TDC and a diagram factor of .9 was used to take into account the rounding of the corners of the pressure - volume diagram.

The variable clearance volume engine would require a displacement of approximately 1.4 cubic inches to meet the power requirements. This engine cycle has about the same SPC characteristics as the variable admission cycle. A variable clearance volume may be difficult to mechanically implement.

The Otto cycle with variable exhaust pressure yields a low BSPC at the power levels of most interest. An engine of approximately 5.5 cubic inches displacement with a 5% clearance volume would be necessary to produce the required power. The large engine size is not necessarily a disadvantage because it reduces the problem of valve clearance which could exist in a smaller engine with a 5% clearance volume. The larger engine may weigh more than a 1.5 cubic inch engine but the decreased BSPC would cause a substantial weight saving for the combined system. The larger engine would also be more reliable because it would not be as highly stressed. There possibly could be a problem of high mean cycle temperature at low power with the variable exhaust pressure cycle.

The Otto cycle with a variable hydrogen inlet pressure is the preferred approach at the present time. It would have the same displacement and clearance volume as the variable exhaust engine with a lower BSPC in the low power range. This engine would also have all the advantages pointed out in the variable exhaust cycle. The regulation of the hydrogen inlet pressure should be easy to achieve mechanically and on the surface there appears to be no problems with this type of engine cycle and control.

b. Heat Rejection Analysis

Regenerative Cycle

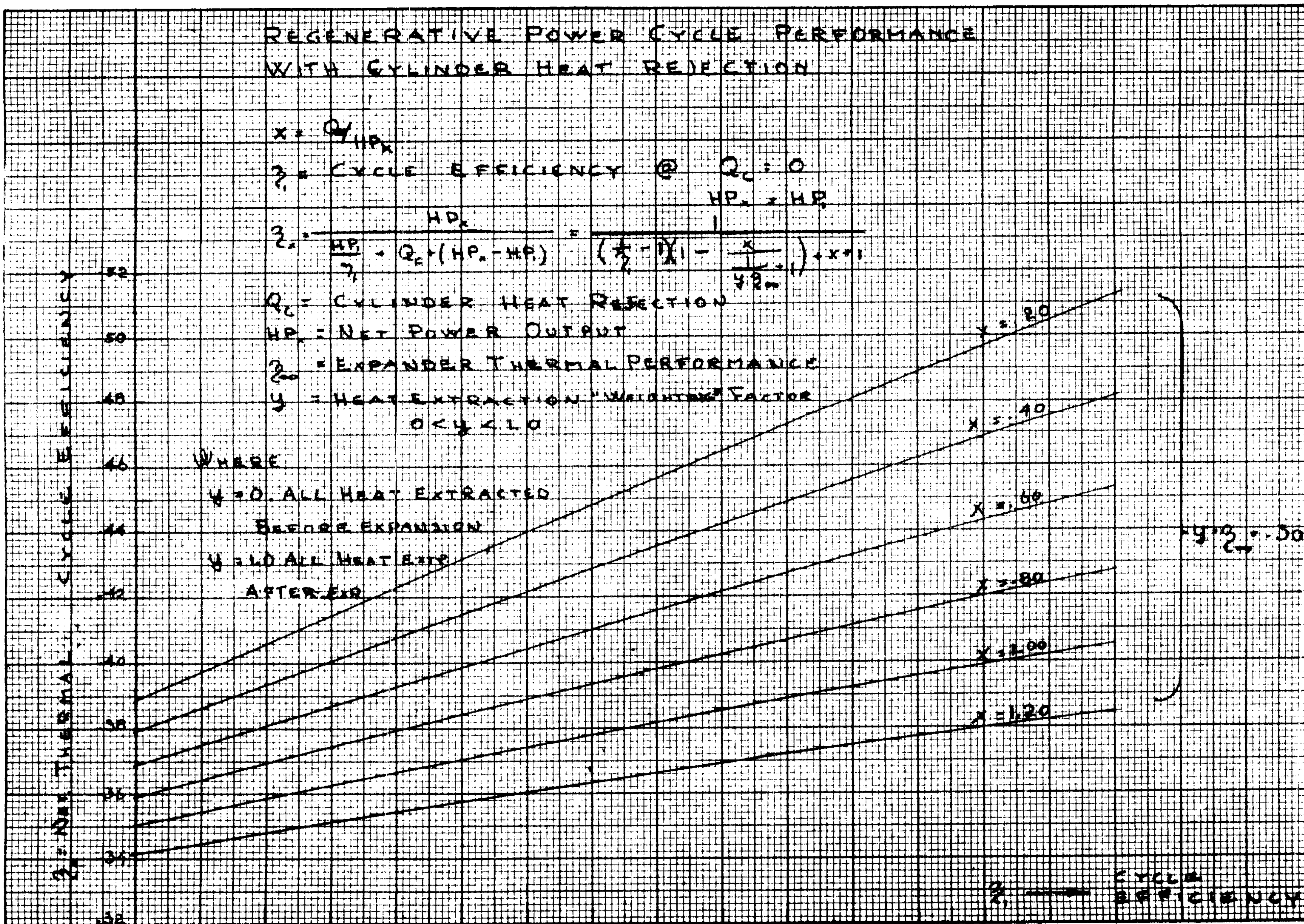
Figure 5 illustrates the effect of cylinder heat rejection on the performance of a regenerative power cycle. As expected, increasing cylinder heat rejection (x) lowers cycle thermal efficiency (η_x). In a typical example η_∞ is assumed to be 0.50. Automotive engine heat rejection data suggests a value of the heat rejection "weighting" factor, y = 0.6 be used and heat rejection rates (x) between 0.4 and 1.0 are considered representative limiting values. Cycle studies at Vickers indicate that cycle efficiency with no cylinder heat rejection (η_i) of about 0.5 are achievable. For this case it can be seen from Figure 5 that when x = 0, $\eta_x = 0.50$; when x = .40, $\eta_x = 0.449$; and when x = 1.0, $\eta_x = 0.389$. BSPC varies inversely with net thermal efficiency (with heat rejection) η_x.

Non-Regenerative Cycle

Non-regenerative cycles are not affected by the heat rejection, which occurs during the blowdown process, while the regeneration process in a regenerative cycle suffers due to this effect. Although quantitative data on the non-regenerative cycles are not available at present, qualitative conclusions can be drawn.

The non-regenerative, stoichiometric engine cycle, will tend to reject less total heat to the cylinder because of the higher molecular weight of the working fluid. Furthermore since the majority (per-

Fig. 5


REGENERATIVE POWER CYCLE PERFORMANCE
WITH CYLINDER HEAT REJECTION
$X = Q_c / HP_x$
η_1 = CYCLE EFFICIENCY @ $Q_c = 0$
$HP_x = HP_1$
$\eta_x = \frac{HP_x}{\frac{HP_1}{\eta_1} + Q_c + (HP_x - HP_1)} = \frac{1}{\left(\frac{1}{\eta_1} - 1\right)\left(1 - \frac{X}{\frac{1}{y\eta_{ex}} + 1}\right) + X + 1}$
Q_c = CYLINDER HEAT REJECTION
HP_x = NET POWER OUTPUT
η_{ex} = EXPANDER THERMAL PERFORMANCE
y = HEAT EXTRACTION "WEIGHTING" FACTOR
$0 < y < 1.0$
WHERE
$y = 0$ ALL HEAT EXTRACTED BEFORE EXPANSION
$y = 1.0$ ALL HEAT EXT'D AFTER EXP
X = .20
X = .40
X = .60
X = .80
X = 1.00
X = 1.20
$y \cdot \eta_{ex} = .50$
η_x = NET THERMAL CYCLE EFFICIENCY
η_1 → CYCLE EFFICIENCY
.52
.50
.48
.46
.44
.42
.40
.38
.36
.34
.32
.40
.45
.50
.55

haps @ 60%) of the heat is rejected during the blowdown process, significantly less effect of heat rejection will be reflected upon the performance of the non-regenerative cycle. It is reasonable to assume that the loss in cycle efficiency with heat rejection in the non-regenerative cycle will be less than the loss in a regenerative cycle with equal rates of heat transfer.

c. Stoichiometric Operation

Early in this program consideration was given to redirecting the effort toward a hydrogen-oxygen system which would operate at stoichiometric mixture ratio and use an internal compression non-regenerative prime mover. The advantages of such a system over the fuel-rich regenerative system include the probability of lower heat rejection, less sensitivity of cycle performance to heat rejection, and lower total system volume due to operating at the stoichiometric mixture ratio. It was felt that the lower system volume would make the system more applicable to a wider range of mission requirements. In discussing these suggestions with the NASA program manager it was agreed that the stoichiometric cycle should be studied further as part of the parametric study phase of this program. In the meantime work would progress along the lines of a regenerative fuel-rich system.

Since that time, preliminary study work on the stoichiometric system has been carried on but the results to date have been somewhat inconclusive. The many gray areas involved seem to indicate that a detailed and rigorous comparative analysis would be required in order to make a completely objective comparison. Such a study appears to be beyond the scope of the current contract without seriously jeopardizing the success of the other phases of the program. Therefore it is recommended by Vickers that no additional comparative analysis with the stoichiometric non-regenerative cycle be conducted in the course of this current program. However it is further recommended that serious consideration be given to that type of system for possible application within the overall spectrum of space power systems. Particularly the internal compression engine either in a two stroke version or a four stroke version appears to offer the advantages of a simpler, more easily developed prime mover for hydrogen-oxygen power systems than does the regenerative external compression type engine regardless of whether it is to be used in a fuel rich application or a stoichiometric application. On the other hand the internal compression engine does not lend itself as readily to achieving high thermal efficiencies as does the external compression regenerative engine.

Controls

a. Evaluation of Technical Requirements

The essential control problem is the control of alternator speed to a constant value, $\pm .5\%$, during a constant load condition, and allowing speed deviations of not greater than 3% during load transients of the magnitude shown on the duty cycle. There are other important problems such as starting, switching systems on line, and fail-safe considerations; but effort on these areas will be delayed until requirements are better known and a speed control configuration has been determined.

b. Evaluation of Engine and Propellant Source Configuration and Operating Characteristics

Information in this area is essential before detail control design can be accomplished. Information needed to attain configurations and characteristics was outlined and requested from the Engine Performance Analysis Group. A continuous coordination effort remains with this group until a mathematical engine model is agreed upon. Such studies are described in the Parametric Studies Section of this report.

The dynamic representation of the engine was given consideration. The basic question in this area was the accuracy of representing the discontinuous combustion and torque cycle of the engine as a continuous, mean, process. The continuous representation was approved, but this decision will be re-evaluated at a later time.

The inertia of the rotating parts was established. The evaluation shows the moment of inertia of the ASD engine and representative alternator and gearing components to be:

Engine	.0159	Lb-Sec^2-in
Alternator	.0072	" " "
Total	.0231	" " "

Indicating an engine acceleration constant of

$$416 = \frac{\partial \, RPM/Sec}{\partial \, L_\Delta}$$

L_Δ = Torque Unbalance in inch lbs.

c. Evaluation of Estimated Control Configuration

Substantial linear analysis is being performed on the over-all system by assuming unknown portions of the system and using a non-dimensional approach. The important relationship between the load input and speed output is known which makes this type of analysis much more useful.

Effort at this point has been concentrated on three system approaches. These are:

System (1) A control system which has the capability of anticipating speed changes before they occur has more time to correct for the cause of the speed change. Sensing load changes and correcting power proportionally to the load changes, as in system (1), gives such capability in controlling engine speed. System (1) would be combined with system (2) or (3) in actual practice, but separate examination helps to establish requirements for systems (2) and (3).

System (2) A control system which adjusts power at rates proportional to the amount of speed error is an integral control system. It has the capability of driving the speed error to zero. Compensation, which is necessary to stabilize the system and provide better response is a form of load change sensing.

System (3) A control system which is the same as System (2) except for a more complex type of compensation.

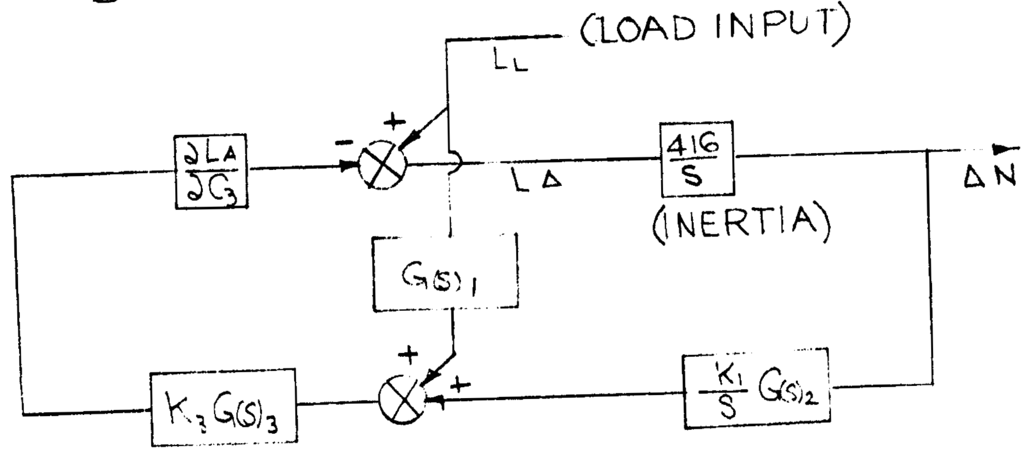
These systems are represented by the block diagram and tabulation of Figure 6.

Although much work remains in evaluating these systems, some conclusions have been drawn.

1. In system (1), load sensing helps but is not sufficient by itself to control step inputs.

Figure 6

BLOCK DIAGRAM FOR LOOP



SYSTEM APPROACHES

SYSTEM	$\frac{\partial L_A}{\partial C_3} K_3$ CONSTANTS	$\frac{K_1}{S}$ INTEGRATOR	$G(S)_3$ POWER CONTROL VALVE DYNAMICS	$G(S)_2$ COMPENSATION	$G(S)_1$ LOAD SENSOR
1	1	0	$\frac{1}{S^2/54400 + S/232 + 1}$	0	$\frac{1}{.02S+1}$
2	$\frac{\partial L}{\partial C_3} K_1 K_3 = \text{CONST.}$	$\frac{K_1}{S}$	$\frac{1}{(S^2/54400 + S/232 + 1)(.01S+1)}$	$\frac{.66S+1}{.0182S+1}$	0
3	$\frac{\partial L}{\partial C_3} K_1 K_3 = \text{CONST.}$	$\frac{K_1}{S}$	$\frac{1}{(S^2/54400 + S/232 + 1)(.01S+1)}$	$\frac{S^2/100 + S/10 + 1}{(.1S+1)(.066S+1)}$	0

2. Increasing rotating moment of inertia will reduce errors in all systems and is desirable from a controls point of view.

3. Judicious selection of compensation will be required in order to meet transient requirements and maintain small amplitude stability. As an example, system (3) has much more comfortable gain and phase margins than system (2).

d. Evaluation of Components

Information is being requested from governor manufacturers and tachometer manufacturers on speed control devices applicable to this problem. Some Vickers experience indicates that power requirements for a hydro-mechanical governor might be large (in percentage) for a small power unit.

Electrical Components

NASA requirements have been reviewed. The load duty cycle furnished by NASA shows load versus time in watts. Vickers is assuming that watts have been specified at a constant power factor of .75. If not, specific power factors corresponding to each load level should be stated by NASA.

General Electric and Westinghouse have been contacted. Proposals from each are expected within 2 weeks. Other vendors will be consulted on components.

Starter: For engine starting tentative selection has been made of a commutator and brush D.C. dual function starter-motor-generator hermetically sealed in an optimum gaseous atmosphere and externally cooled by the system fluid coolant. Torque transfer is accomplished by the use of high coercitivity permanent magnets, one affixed to the motor shaft within the hermetically sealed space, and the other affixed to a gear shaft common to the alternator drive gear train. The speed of the motor is high, hence the torque requirements of the magnetic coupling are small. The D.C. starter-generator shall function as a generator, without the use of switching devices, to maintain the system battery at optimum voltage.

Reliability Studies

Since the reliability of a particular power system depends to such a large extent on the detail system configuration including component types and other detail design considerations, it has been decided to delay the reliability study phase of the program until the basic system configuration is better defined. In the meantime a literature search has been initiated to obtain data on failure rates of piston engines, particularly for aircraft applications and on generators, compressors, and other components, such as controls, which may be selected for use in the final system configuration. It is expected that more detail consideration of the reliability aspects of the system design will get underway in the near future as the system configuration becomes better defined.

Materials

Material studies conducted to date have been limited to selection of materials for the various pieces of experimental hardware to be constructed during this program. Particular attention has been given to materials for use in the difficult areas application such as operation at the very low temperatures to be encountered in the cryogenic hydrogen compressor and to the high temperature oxidizing atmosphere conditions to be encountered in the oxygen injector.

Hydrogen Compressor

The design and detailing of the experimental hydrogen compressor has been completed. Drawings have been released to the shop for fabrication of an experimental unit. The design of this hydrogen compressor was described in the progress report for July 1962. However a few minor design details have been changed during the month since that report was written. The final design configuration of the compressor is shown in Figure 7. Areas in which the final configuration differ from the preliminary design shown in the July progress report include separate cylinder heads for ease of assembly and convenience in testing different cylinder configurations and materials. A poppet valve was selected for the first stage inlet valve because it was felt that this type of valve would be easier to manufacture successfully than the reed type valve which was shown on the preliminary design drawing. The inlet and discharge valves for both stages are now located in the cylinder heads in order to simplify the construction of the cylinders and to avoid conflicting material requirements which might be associated with attaining cylinder wear resistance and valve seat impact resistance. Aside from these changes the final compressor design is essentially the same as was shown in the July progress report.

Regenerator

Preliminary design of the regenerative heat exchanger has been started but is not far enough along as of this date for any drawings or calculations to be included in the progress report. However the design of the experimental regenerator as a piece of hardware does not appear to be particularly difficult and it is being analyzed in a conservative manner by using some simplifying assumptions. In designing the regenerative heat exchanger it should be noted that in a power system operating in space a sonic velocity will exist in the exhaust system at the point of final exit to space. Existence of sonic velocity at the end of the exhaust pipe does not necessarily

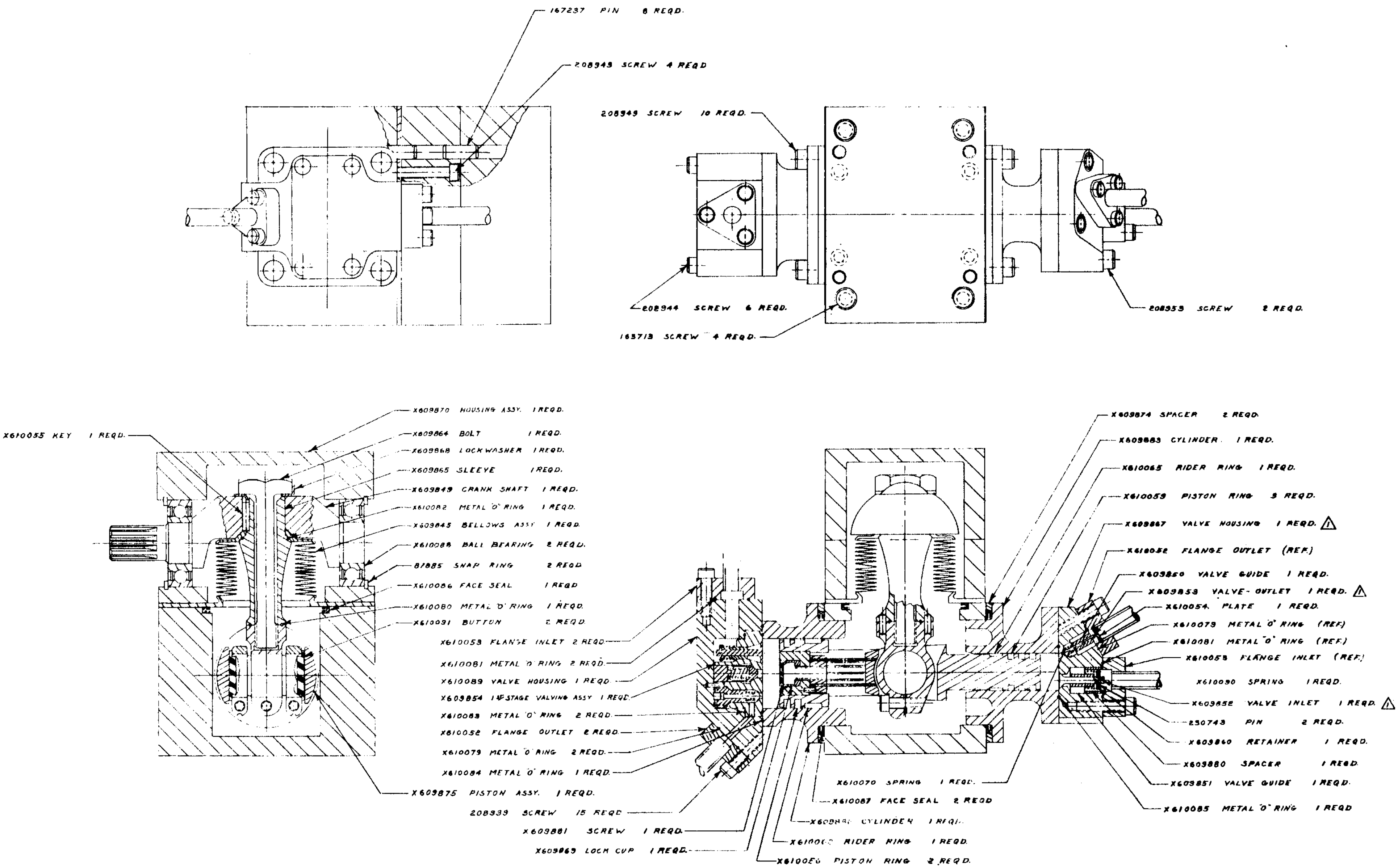


Fig. 7 - H_2 Compressor Assembly

indicate that sonic velocities will not also occur upstream in the system. However if variations in flow area are avoided in the system all upstream velocities will be in the subsonic region. Although it may appear desirable to take advantage of the vacuum of space and operate the exhaust side of the regenerator at high mach numbers, calculation of film coefficients under these conditions is virtually impossible. This is because film coefficients are generated and derived from empirical data which are quite meager at high mach numbers and the presence of pulsating flow tends to further complicate the problem. Therefore it is planned to analyze the experimental regenerator assuming that the exhaust system is equipped with an orifice which chokes at sonic velocity and insures that all regenerator passages are subsonic and within the realm of background data. It can be shown that these are conservative assumptions. In order to facilitate testing of the regenerator it is planned that the design will be based on sea level back pressure conditions. It can be shown that a regenerator designed for sea level condition will improve in performance under space conditions. However a heat exchanger designed for space would be somewhat lighter in weight. At this point of the program light weight is not particularly significant but designing for sea level operation will avoid test facility difficulties which would be encountered in trying to simulate space conditions.

Engine

All drawings for the fabrication of an additional engine of the ASD design have been released with the exception of a few parts which have been the subject of additional design studies. Areas which have been redesigned include the hydrogen valve spring arrangement, the methods of sealing around the hydrogen inlet, and the cylinder head and piston dome construction. Detail drawings for the parts involved in these redesigned areas are being prepared now and will be released during September. Figure 8 shows the revised configuration of the hydrogen valves and hydrogen inlet port. This area was redesigned in order to improve the

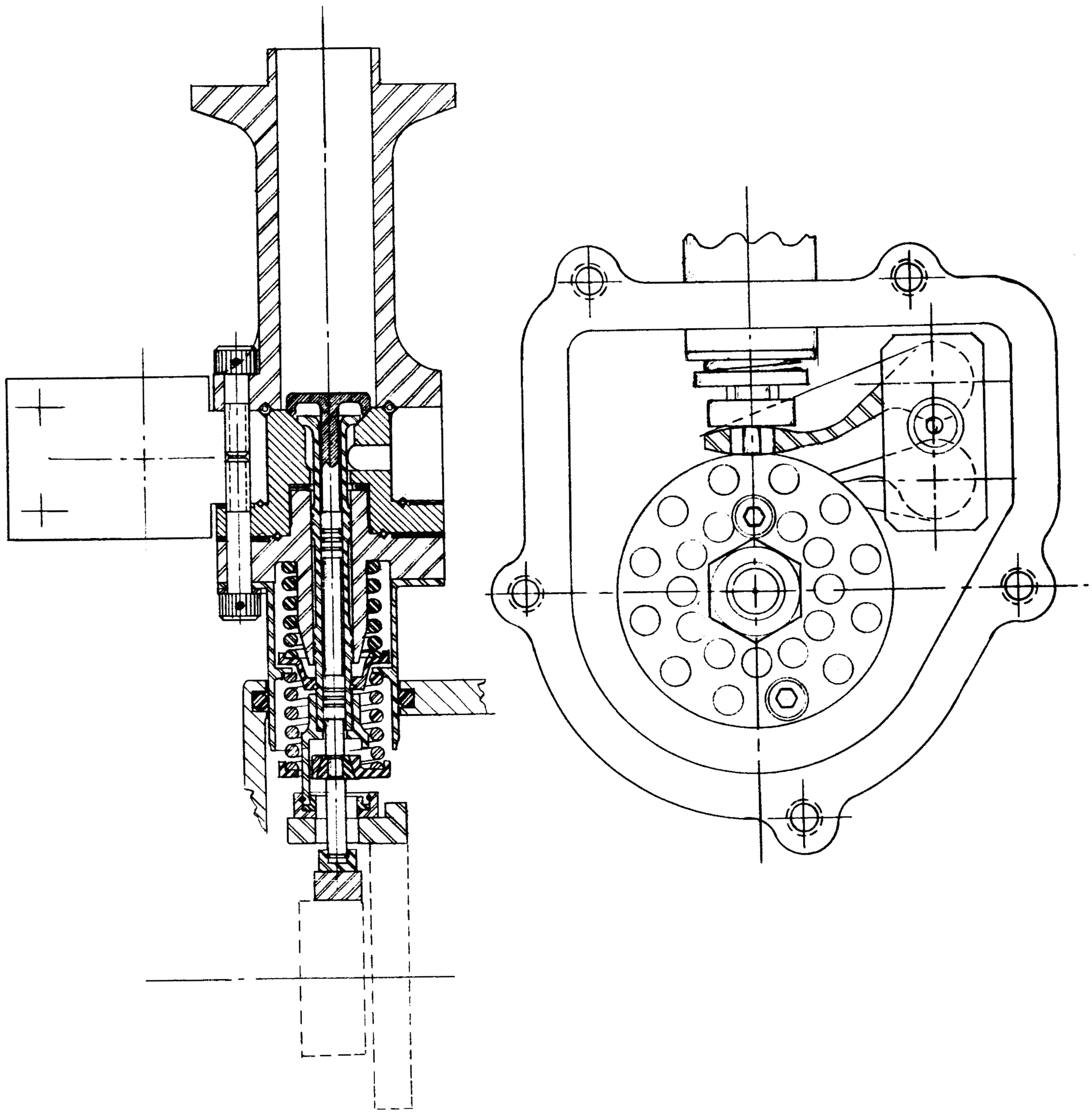


Fig. 8 - H_2 Valve Modification

ease of assembly by making it possible to assemble the valves, valve guide, valve springs, spring keepers, and rocker arm followers on the bench before installing the assembly in the engine. In addition the total number of parts has been reduced from the previous design. The arrangement of the hydrogen inlet adapter has been modified in order to be consistent with the bench assembly of the valves and also to reduce the possibility of leakage from the supply line either to the outside of the cylinder head or by by-passing the valves into the combustion chamber as was possible on the original design. Figures 9 and 10 show alternate arrangements of the cylinder head and piston dome construction. These differ from the original engine design in that they utilize simpler construction and different means of sealing gas pressure in the combustion chamber. As before care has been taken in the design of these parts to minimize the available path area for heat transfer through either the cylinder head or the piston dome. The purpose of this is to attempt to achieve higher cycle efficiencies by reducing overall engine heat rejection. Figures 9 and 10 differ primarily in the method of sealing gas into the combustion chamber. Figuration of Figure 10 was selected as being more desirable because it utilizes static K type seals instead of the metal o-rings as shown in Figure 9. It was felt that problems might occur with the metal o-rings as result of differential thermal expansion between the two surfaces contacting the seal. This is less likely to be a problem area with the K type seal as shown in Figure 10. Engine cylinder material will be changed to a high temperature alloy in order to provide a better chance of operating with high cylinder wall temperatures. In addition the cooling jacket for the upper portion of the cylinder has been redesigned and now takes the form of a helical passage making several passes around the circumference of the cylinder. Previously there was no attempt to direct the flow of water through the cooling jacket. Aside from the changes specifically mentioned here the engine being constructed under this program is essentially identical to that constructed under the ASD contract.

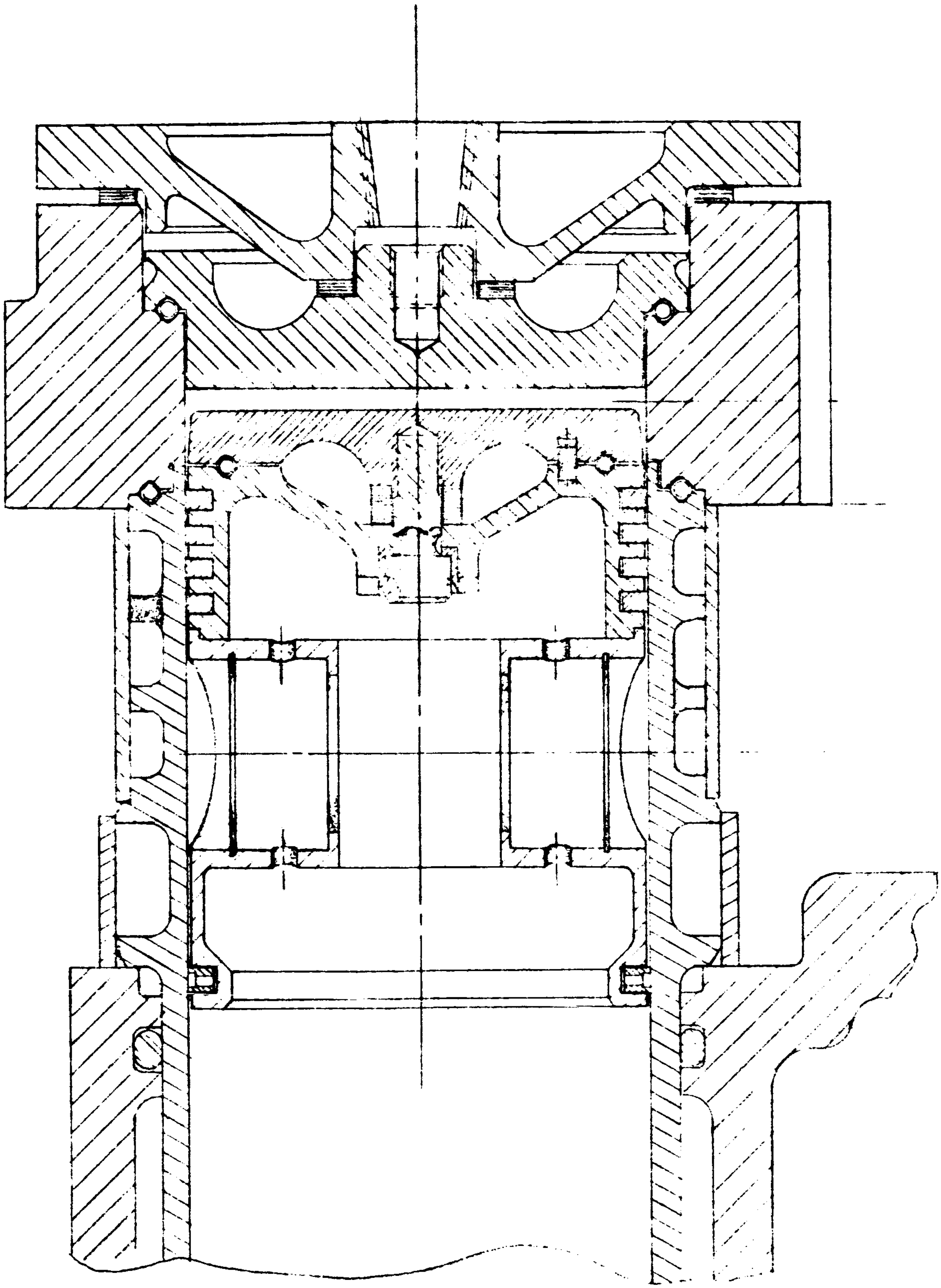


Fig. 9 - Piston and Cylinder Head Configuration

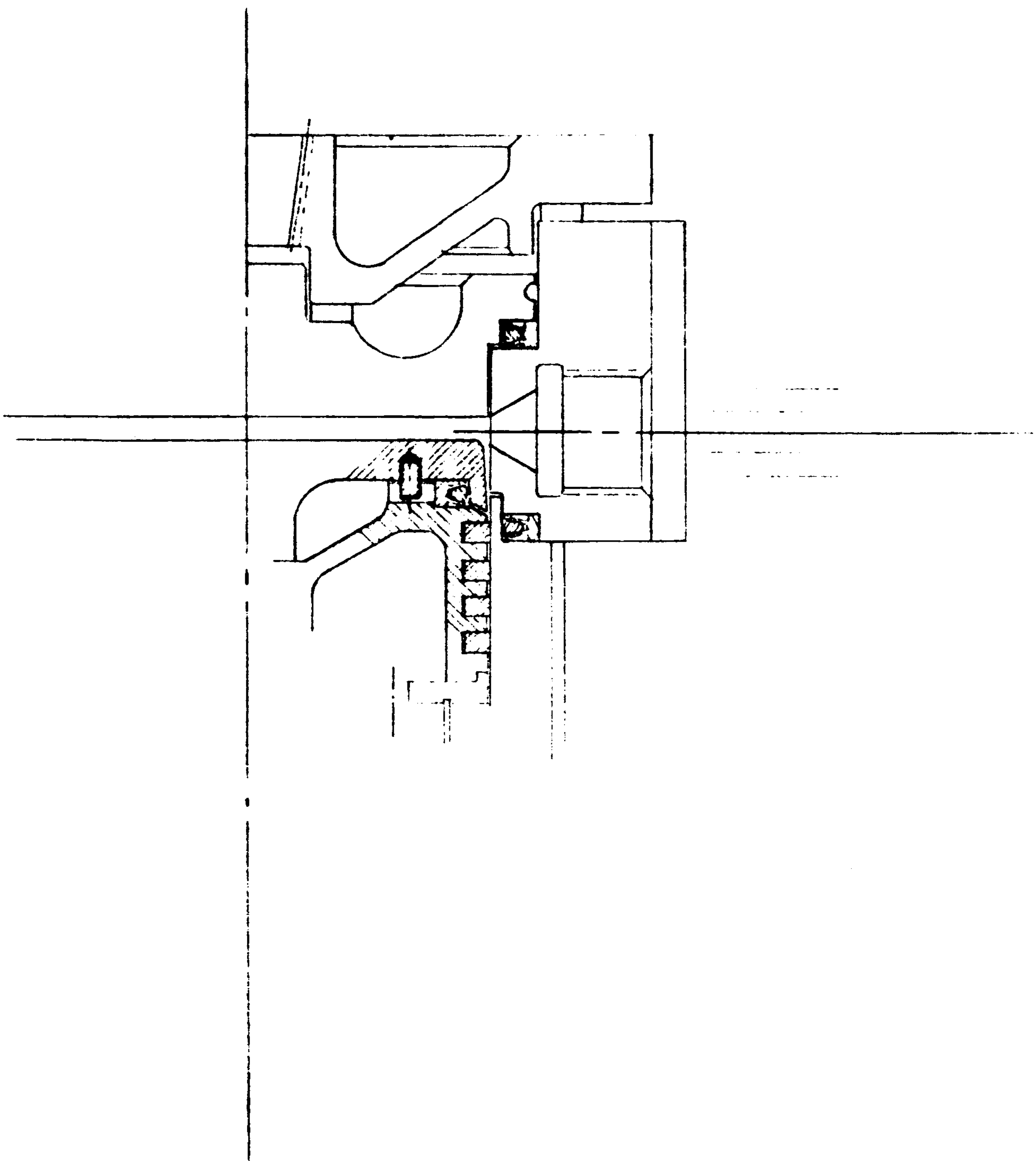


Fig. 10 - Revised Sealing Configuration, Piston and Cylinder

Oxygen Injector

A new oxygen injector has been designed for use in this program both as a part of the engine and for additional development as a component. Separate development of the injector as a component was deemed necessary because of the special problems involved in the development of the injector and because of its importance in achieving satisfactory engine operation. The new injector configuration which is shown in Figure 11 follows the same basic concept as that of the injector design under the ASD program. However a number of worthwhile improvements have been designed into the new injector. In order to reduce the valve seating loads on the injector poppet seat a novel construction has been evolved which allows the inertia loads of the entire actuating system with exception of the poppet itself to be taken on the cam and the inertia load of the poppet valve alone being reacted on the valve seat. By additional changes in the construction of the oxygen injector it is now possible to completely assemble the injector unit on the bench and then install it in the engine as a module. Other improvements in the new design include self-contained bearings for the cam follower shaft, a longer torsional seal tube in order to allow operation at lower stress levels, and a much more rigid support for the flex pivot joint located within the sealed chamber. With proper selection of materials for the poppet and seat it is considered that this new design has a good chance of over-coming the problems which existed in the earlier oxygen injector.

In addition to the design work involved in the oxygen injection configuration shown in Figure 11 some design study effort was devoted to an alternate oxygen injector design which differed basically from the hermetically sealed unit shown here. This alternate design consisted of arranging a small poppet valve for admitting oxygen into the cylinder in a manner similar to the arrangement of the hydrogen valves. However this configuration did not appear to offer enough advantage over the configuration shown in

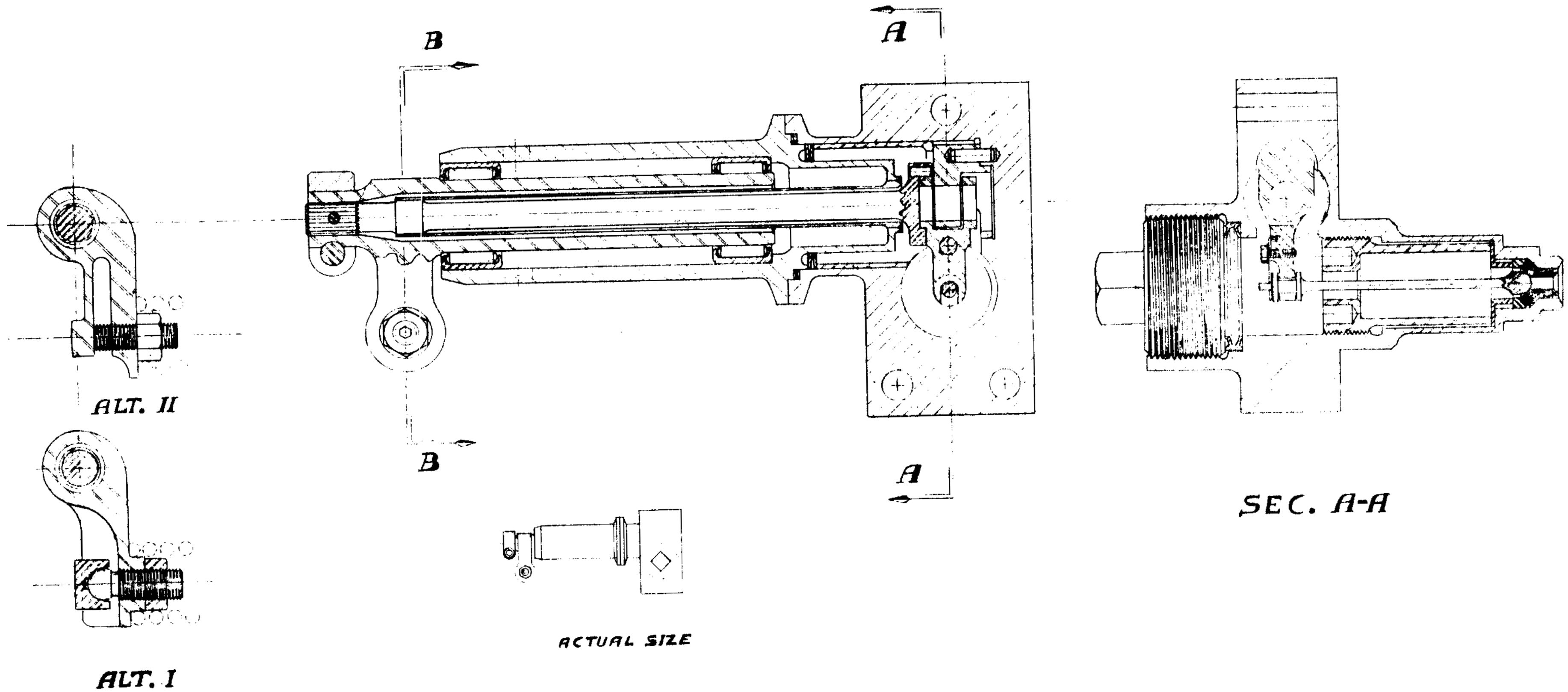


Fig. 11 - O_2 Injector Design Modification

Figure 11 to justify continuing that design approach. Therefore it was decided to build and test the oxygen injector configuration shown in Figure 11.

PROBLEM AREAS AND SOLUTIONS

The major problem area encountered to date in this program is that of helium dilution of the oxygen available as boiloff from the main propulsion tankage. Helium dilution of the hydrogen boiloff gas does not appear to be a serious problem within the range specified by NASA. Since operation of the system is at a hydrogen-rich mixture ratio the presence of helium merely reduces the amount of hydrogen necessary to act as a combustion temperature limiting diluent. However the problem is much more severe with helium dilution of the oxygen and it appears unlikely that very large percentages of helium can be tolerated in the oxygen boiloff gas without excessive system complexity. Study of this problem is continuing and results will be discussed in future reports.

Other problem areas which have been encountered are those of material selction for the critical areas of the components to be built in this program such as for the cryogenic hydrogen compressor, the oxygen injector, and the high temperature areas of the engine.

PLANNED FUTURE WORK

For the forth coming report period it is planned to continue work in all of the areas of the program as indicated in the schedule in Figure 1. Parametric studies, controls analysis, and selection of electrical components will continue. Reliability and failure analysis will begin and material studies will continue as required for selection of materials for the experimental components. Fabrication of the experimental compressor and engine will continue as scheduled. Drawings will be released for fabrication of the experimental oxygen injector, and it is expected to complete the preliminary design of the experimental regenerative heat exchanger within the forthcoming period.